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Active Propellant Management

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Operating spacecraft at End-Of-Life (EOL) presents a lot of challenges. For spacecrafts with multi-tank propulsion system, one of the problems is propellant migration between tanks due to temperature difference between tanks, so called thermal pumping. Propellant migration can deplete one of the tanks even though the total propellant load of the spacecraft does not indicate any possibility of tank depletion. The thermal pumping should be taken into consideration at EOL when amount of propellant migrating in and out of the tank is comparable with propellant load of a single tank. The paper discusses an Active Propellant Management (APM) approach to control propellant migration in order to reduce risk of an accidental depletion of a single tank in multi-tank propulsion system. A reduction of the propellant migration is accomplished by using tank heaters to control propellant movement between tanks. The paper discusses possible APM implementations, like temperature difference driven vs. time line driven. It shows that the most common approach, namely, temperature difference driven APM may lead to a more dangerous propellant distribution than it tries to mitigate. The paper also discusses effect of propellant migration on re-pressurization procedures for satellites with blow-down multi-tanks propulsion system.

I. Introduction

For spacecrafts with multi-tank propulsion system, when tanks have one common point, propellant migration between tanks due to temperature difference between tanks creates some problems. One of them is change a center of gravity of a spacecraft due to mass imbalance between propellant tanks, which could be a problem for imaging spacecrafts. Constant propellant migration between tanks may lead to spacecraft wobbling and reduction in image quality.

Diurnal propellant migration between tanks can also create a problem for tank re-pressurization. Typically, in blow-down propulsion systems, propellant tanks need to be re-pressurized at least once due to drop in pressure. If tanks are not balanced during re-pressurization, the pressuring gas load will become different in different tanks which may lead to further tank propellant load imbalance. Such an imbalance may be a concern for spacecraft operation at End-Of-Life (EOL).

Propellant migration presents additional challenge for spacecraft operation at EOL. Propellant migration (thermal pumping) can deplete one of the tanks even though the total propellant load of the spacecraft does not indicate any possibility of tank depletion. The thermal pumping should be taken into consideration at EOL when amount of propellant migrating in and out of the tank is comparable with propellant load of a single tank.

The paper discusses an Active Propellant Management (APM) approach to control propellant migration in order to reduce risk of an accidental depletion of a single tank in multi-tank propulsion system. Reduction of the propellant migration is accomplished by using tank heaters to control tank temperature. It

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could be done using temperature difference between tanks, which is the most common approach, or it could be done by schedule. The paper discusses possible APM implementations and efficiency of temperature differential control to mitigate risk of tank depletion.

II. Problem

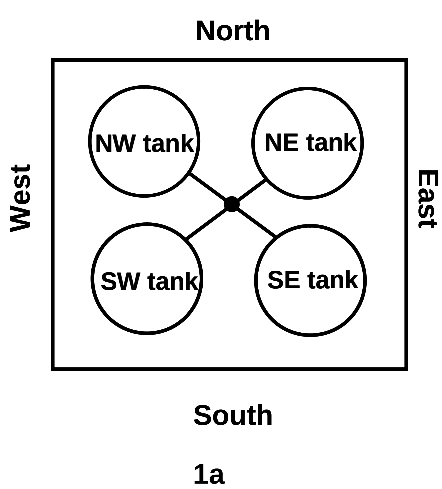
In multi-tank propulsion system, propellant tanks have a common point through which tank are connected. In blow-down propulsion systems, which are typical for satellites, propellant tanks are filled with a gas at high pressure, mostly Helium. When tanks are at different temperatures, propellant moves from warmer tanks to tanks at lower temperature due to difference in pressuring gas pressure. Temperature difference between propellant tanks stems from the fact that different sides (East/West) of satellite periodically exposed to the Sun light daily due to an orbital movement. Also, GEO satellites experience seasonal temperature difference between North and South sides.

At the End-Of-Life (EOL), propellant migration due to temperature difference (thermal pumping) between tanks can cause serious concern because amount of propellant migrating in and out of the tank is comparable to propellant load of a single tank. This can lead to accidental tank depletion if the propellant level in the tanks drops below certain level and Helium can enter into a tank outlet.

The goal of the APM is to minimize thermal pumping in order to reduce risk of accidental tank depletion. Several factors like tank propellant load, season, etc. affect APM implementation. The effect of the factors on APM efficiency is discussed in the paper.

Let us consider a blow down propulsion system which consists of four connected propellant tanks. Such a propulsion system is used in LM 5000 bus[1]. Some propulsion systems have 2 tanks connected, which is mostly common for by-propellant propulsion systems. Propulsion system of BSS 601 s/c presents a typical example of such the bi-propellant propulsion system[2]. Results of current study are also applicable to a propulsion system with two connected tanks, which is simpler than four connected tank system.

Let's consider four tank system schematic of which is depicted in Fig.1a. The model of a single tank is shown in Fig.1 b. For the sake of simplicity, the tank is considered consisting of gas and liquid portions thermally interacting with each other and tank wall. The tanks have capillary driven Propellant Management Device (PMD), which typically consists of vanes and a sump at the bottom of the tank. An outlet pipe is connected to the sump. The tanks are covered with MLI and thermally interact with satellite environment via radiation and conduction.



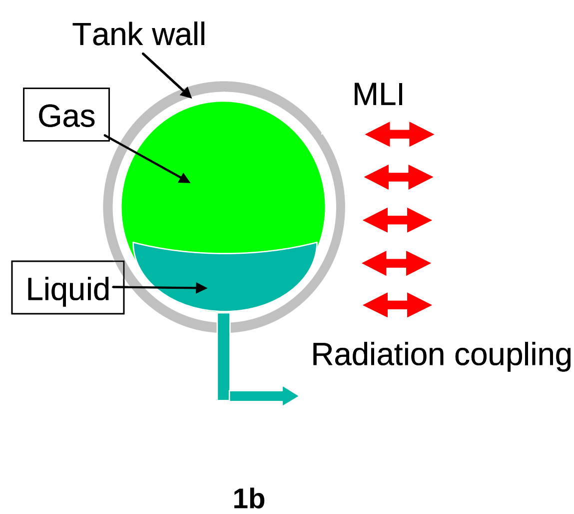


Figure 1. Spacecraft and tank configuration

East/ West side tanks experience diurnal temperature variations. North/South side tanks experience seasonal variations, namely, the South tanks are warmer than North sides tanks during Winter Solstice. The situation is reversed during the Summer Solstice when North side tanks are warmer than the South side tanks.

A spacecraft model which includes four connected tanks was developed using SINDA/Fluint software tool. Each tank was represented by several nodes which include fluid and gas, tank wall and MLI. Tanks are connected by pipes and have a common point. Tanks interact thermally with spacecraft panels.

III. Results

Let's consider propellant migration during the Winter solstice at EOL when the migration can cause tank accidental depletion. Figure 2 shows a typical propellant movement between tanks during winter solstice due to diurnal temperature variation. Temperature difference between tanks takes place not only between East/West sides but also between North/South sides during the solstice. It is assumed that tanks have had even load distribution initially. It means that tanks would have the same load at the case of no temperature difference between tanks. As one can see, the South side tanks have less averaged load than the North side tanks. For example, South tanks (SE or SW) have 1 kg less on average than North tanks during Winter Solstice. Also, the total migration of the propellant in and out of a tank is about 1 kg which constitutes 1/3 of the average tank load. The data presented on Fig.2 clearly identifies the South side tanks as most likely tanks where accidental depletion can happen.

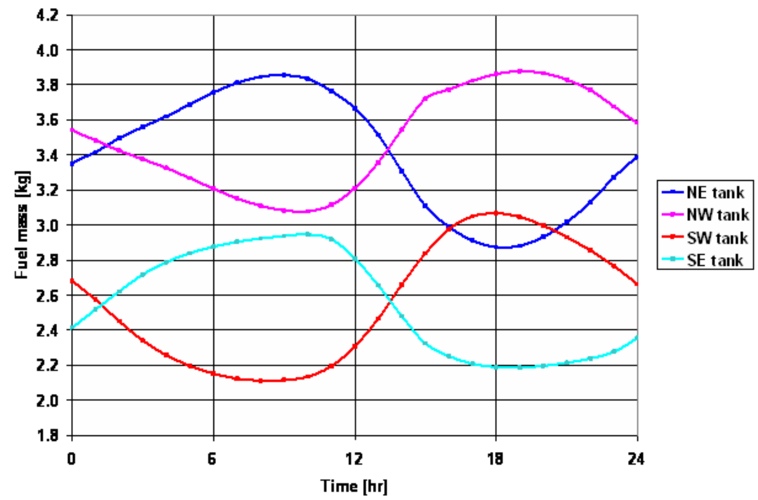


Figure.2 Diurnal propellant migration between tanks during Winter Solstice

Gas penetration into engine feed system may occur during spacecraft maneuvering as Fig. 3 shows. Propellant shifts during satellite station and the sump can get exposed to gas at this time. Gas can enter the outflow line if bubble point of the sump is exceeded. In the case shown in Fig. 2, the highest probability of such an event will be for the South side tanks when the tanks load is at the lowest level.

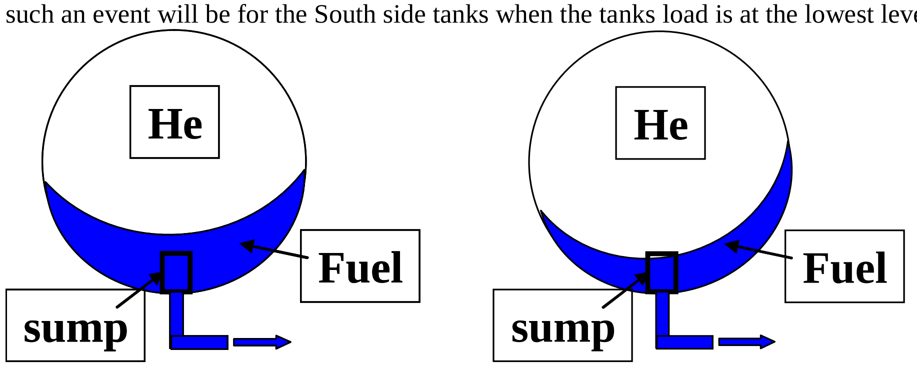


Figure 3. Propellant position in the tank.

In order to reduce the risk of gas digestion by the engine feed system, amount of propellant in the tank should be enough to have sump covered all time regardless of whether a satellite has station keeping maneuvers or not. We will call such minimum propellant load as the Minimum Allowable Propellant Load (MAPL). If the tank load is less than the Minimum Allowable Propellant Load (MAPL), the gas digestion by the feed system can happen during station keeping maneuvers.

It is obvious, that the maximum amount of propellant migrated out of the tank should not reduce the tank load below MAPL. We will call such maximum amount of propellant as the Maximum Allowable Propellant Migration (MAPM). Figure 4 demonstrates the Minimum Allowable Propellant Load (MAPL) and the Maximum Allowable Propellant Migration (MAPM) concepts. The Minimum allowable propellant load *determines* the Maximum Allowable Propellant Migration. One can see, that MAPL and MAPM should satisfy relationship :

MAPL = average tank load – MAPM

The goal of the Active Propellant Management is to reduce MAPM for given average tank load in order to reduce risk of gas accidental digestion by the engines feed system.

We will consider two approaches for APM. According to one of them the APM is driven by tank temperature difference between tanks on West and East sides. Other approach uses time line for propellant management in order to increase the minimum propellant load.

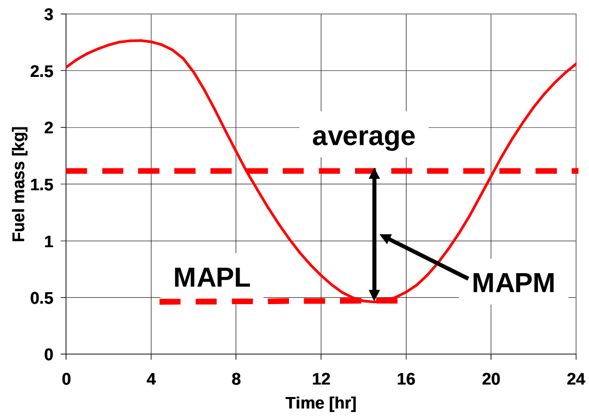


Figure 4. MAPL and MAPM concepts

A. APM driven by East –West temperature difference

Data in Fig. 5 shows the temperature difference between the tanks when the APM is designed to keep the temperature difference between tanks at 3C dead band. The tank heater status is also shown in Fig. 5.

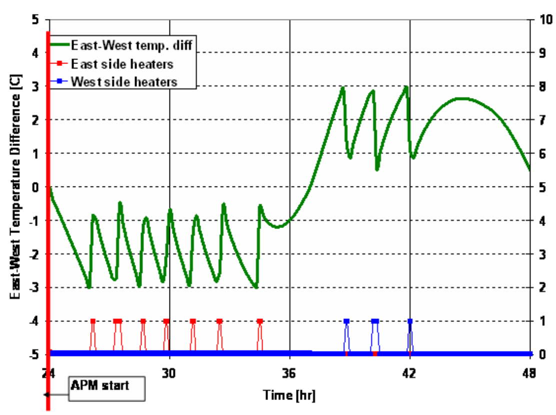


Figure 5. Temperature difference and heater status during 24 hr period

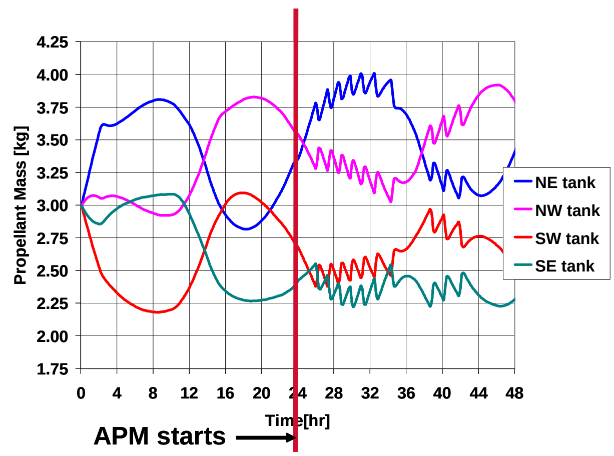


Figure 6. Effect of APM on propellant migration. APM is driven by temperature difference between tanks on East and West sides

As one can see, the East side heaters are turned ON and OFF during first half of the day, when sun shins on the West side of the satellite to maintain 3 C difference between tanks on the East and West sides. The East side heaters are turned ON and OFF during the second half of the day.

Figure 6 shows an effect of APM on propellant load of the tanks. As one can see, the propellant migration has being reduced by APM driven by temperature difference but the minimum propellant load does not change much. The minimum propellant load of SE tank does not change with APM in effect, namely, the minimum load is around 2.3 kg regardless of APM. It means that the propellant load is kept at low level and risk of accidental gas digestion is **NOT** reduced.

B. APM driven by time line

Other approach to APM is to turn heaters ON and OFF according to pre-determined schedule. Figures 7 and 8 show the effect of the APM on tank propellant load when heaters turned twice or 4 times a day correspondingly.

As one can see, the APM driven by the time line produces reduction of propellant migration where it is needed (f. ex., IN&OUT of South tanks vs. North tanks during Winter solstice). It also provides more flexible control over propellant distribution between tanks, e.g., schedule can be devised to increase minimum propellant level in order to reduce risk of gas digestion. As data in Fig.8 indicates, increase number of heat pulses reduces propellant migration.

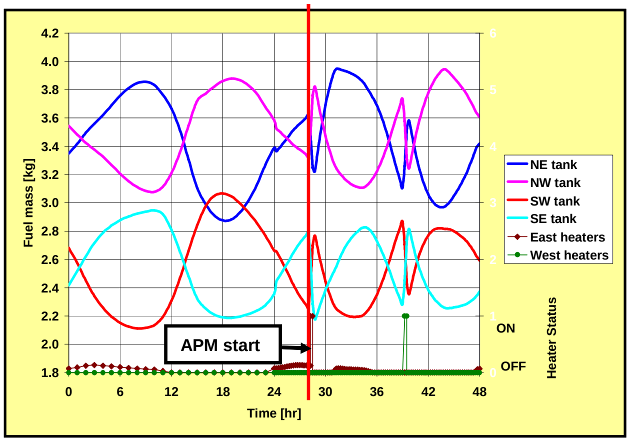


Figure 7. Heaters on WEST or East sides turned ON/OFF ONCE a day.

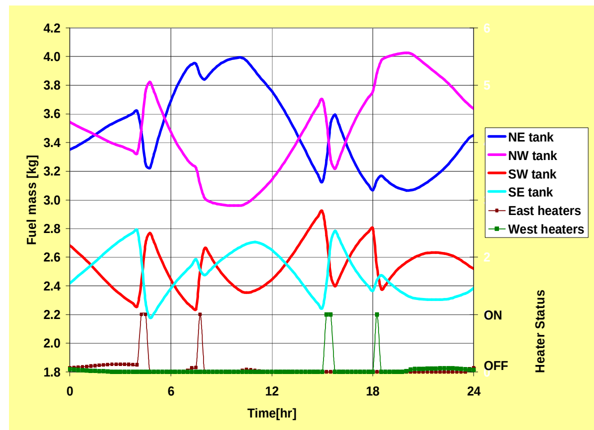


Figure 8. Heaters on WEST or East sides turned ON/OFF TWICE a day

Re-pressurization

Diurnal propellant migration between tanks can also create a problem for tank re-pressurization. Typically, in blow-down propulsion systems, propellant tanks need to be re-pressurized at least once due to drop in pressure some times at the middle of life. Even for propulsion systems where only two tanks are connected, like bi-propellant, the propellant migration results in difference in tank load through out of the day due to diurnal temperature variation. The matter is getting even more complicated if connected tanks situated on opposite corners of the satellite, like NE corner and SW corner of the satellite (see Fig. 1a).

A season also affects propellant distribution between tanks. If tanks are not balanced during re-pressurization, the pressuring gas load will become different in different tanks which may lead to further tank propellant load imbalance. Such an imbalance may be a concern for spacecraft operation at EOL.

Figure 9 shows the correlation between tank wall temperatures and fuel mass for two tanks situated on opposite corners of the spacecraft, NE and SW tanks. Temperature of two portions of the tank wall is shown, namely, the wet wall which is against fuel and the dry wall which is

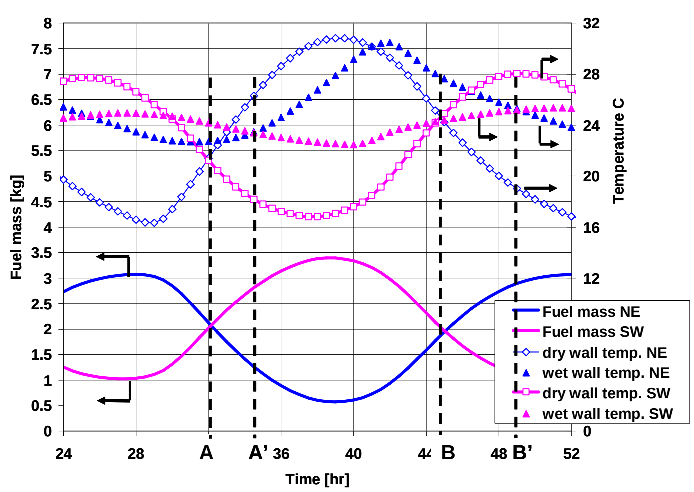


Figure 9. Correlation between tank wall temperatures and tank fuel loads.

against Helium (see Fig.1b). As data indicates, use of temperature sensor reading to figure out the time when tanks have equal mass could be misleading. If the temperature sensor is installed on the dry portion of the wall, the time when tank masses are equal is the same as time when temperature readings are equal (times A and B). On other hand, if the temperature sensor is installed on the wet portion of the tank, which is common, time of equal temperature (time A' and B') does not correspond to the time of equal mass (time A and B). The time lag can be up to 4 hours as Fig. 9 shows. Equality of temperature readings at some point does not guarantee that propellant load of the tanks is the same at that point. In order to make sure that tanks have almost equal propellant load during re-pressurization, the study similar to one conducted in this paper should conducted.

IV. Conclusion

The Active Propellant Management decreases diurnal propellant migration which should reduce a risk of accidental gas digestion into the feed system. Out of two APM implementations, namely, the temperature driven and time-line driven, the APM driven by time-line provides more control over propellant movement between tanks then typical APM driven by temperature difference. At certain conditions, typical APM driven by temperature difference does NOT reduce risk of tank accidental depletion.

Driven by schedule APM is more flexible and can be designed to achieve certain goals, e.g. reduction of propellant movement or increase the minimum of propellant level. This approach can be used for balancing propellant load of the tanks during solstices.

Use of temperature reading as indicator of the appropriate time for re-pressurization should be done with some caution because the fact that temperature of tanks are equal does not necessarily mean that propellant loads are equal. The correlation between temperature and mass equalization greatly depends on the temperature sensor location.

V. Reference:

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[2]G.P. Purohit, C.C. Vu, V.K. Dhir , Transient Lumped Capacity Thermodynamic Model of Satellite Propellant Tanks in Micro-Gravity, 37th AIAA/Aerospace Sciences Meeting and Exhibit, January 11 - 14,1999 / Reno, NV, paper AIAA 994088